ACOUSTIC MEASUREMENTS ON VORTEX STREETS BEHIND CIRCULAR CYLINDERS AND FLAT PLATES

R. Lehnert

Translation of "Akustisches Messungen an Wirbelstrassen hinter Kreiszylinder und ebener Platte," Physikalische Zeitschrifte, Vol. 38, 1937, pp. 476-498

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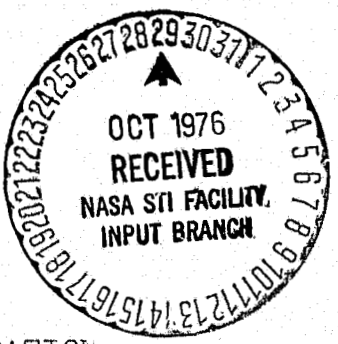

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16. Abstract

Vortex frequencies and distances between successive vortices were measured behind circular cylinders and flat plates exposed to a flow a different angles of incidence. Resonance detection and Pitot tube listening were the two methods used for frequency determination. Resistance is measured with a balance. It is found that the dimensionless vortex frequency $\frac{ND}{U}$ is a function of the Reynolds number, as is also the resistance coefficient c_w. Vortex frequency anddistance between vortices are functions of the distance behind the plate.

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ACOUSTIC MEASUREMENTS ON VORTEX STREETS BEHIND CIRCULAR CYLINDERS AND FLAT PLATES

R. Lehnert[1]

Chapter I: Introduction

1. Practical Significance of Vortex Frequency Measurements and and Resistance Measurements

The shedding of vortices near geometrically simple bodies is /477* of special interest from the point of view of practical construction. Vortex formation is the principle cause of hydrodynamic resistance as long as frictional resistance can be disregarded. In a fundamental work von Kármán has clarified the connection between resistance and vortex street structure (see below). The regularity of vortex shedding, which, on the one hand, makes possible an approximate calculation of resistance, on the other hand presents a considerable threat to stability if the shedded vortices can excite the body to resonance vibrations. So in the construction of aircraft it is necessary to know the behavior of the flow around stays, push rods, etc. which are exposed to the air flow. For antennas and overhead lines, in addition to resistance, the danger of this resonance vibration plays an important role. These are also important matters to consider when we are dealing with buildings (high towers, smokestacks, scaffoldings and stays for gas reservoirs). Vortex shedding on stays and the like is also beset with a certain amount of noise abatement problems.

2. Previous Studies on Vortex Shedding on Circular Cylinders and Flat Plates

In his studies of aeolian tones Strouhal [1] realized that

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1. Department of Applied Mechanics and Thermodynamics at the Physical Institute of the University of Leipzig.

* Numbers in the margin indicate pagination in the foreign test.

periodic air movement caused by "discontinuous shearing of the air" is to be viewed as the cause of sound production on rods set quickly in motion as well as on wires in an air flow. On the basis of his experiments with circular cylindrical rods and wires which, by means of whirling arm he moved approximately translatory normal to the axis through the air, he discovered the relationship

$$\frac{ND}{U} = \text{constant},$$

where N = sound frequency, D = diameter and U = velocity of the cylinder. For small velocities and small diameters, i.e. for small Reynolds numbers, he got systematic deviations. His results were obtained partly by listening to the aeolian tones themselves, partly by determining the particular frequency of the wires excited by the aeolian tones to resonance vibrations.

The theories of hydrodynamic similiarity first shed light on the mechanism of this periodic air movement, as did also, in particular, the theoretical and experimental findings on the structure of the wake of a body moving in a liquid. Accordingly, the dimensionless $\frac{ND}{U}$ is a function of the Reynolds number $Re = \frac{UD}{\nu}$ (ν = kinematic viscosity).

Rayleigh [2] shows it is a function of the Reynolds number by expanding $\frac{ND}{U} = f(\frac{\nu}{UD})$ in a series which he breaks off with the second term and the constants for which are obtained from Strouhal's measurements. He finds good agreement between his equation and Strouhal's results (Fig. 1).

Benard [3] , from detailed flow observations using an optical method he developed, was the first to show the regular ordering of vortices into vortex streets behind bodies in a flow.

Von Karman [4] , using the method of small vibrations, has shown theoretically that there is a stable, asymmetrical ordering of the vortex pattern with the stability condition $\frac{h}{l} = 0.281$

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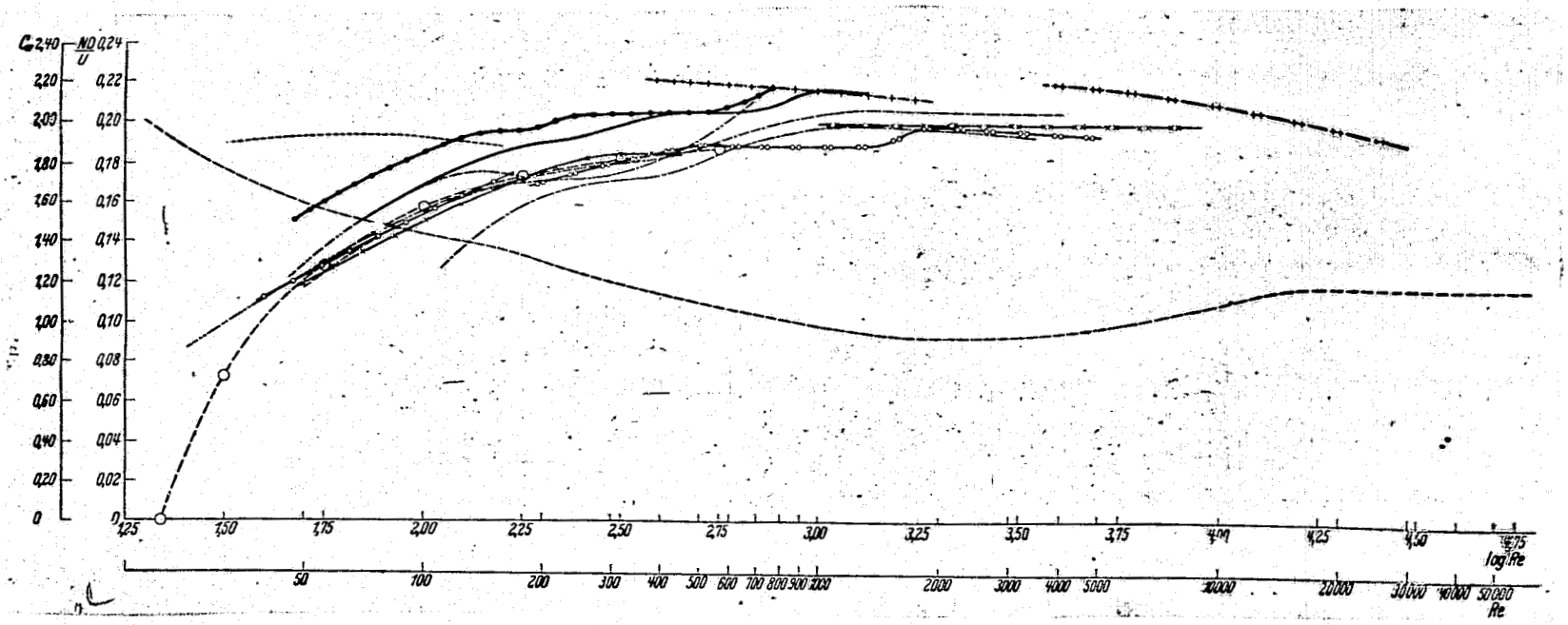

Fig. 1. Vortex frequencies and resistance coefficients of circular cylinders perpendicular to the flow (mean curves)

—0— } Strouhal { Resonance tones } (whirling arm)
—∞— } { Aeolian tones }

--0-- Rayleigh (series expansion with constants from Strouhal's measurements)

----- Krueger (vibrating cylinder in water)

—·—·— Relf (whirling arm; stationary cylinder in water with oscillation analyser)

—·—·· Thom (oscillating cylinder in water)

·-·-· Tyler (whirling arm; hot-wire in air and water; obs. of powdered surface of liquid)

--·-·-- Tyler (Pitot tube)

-x-x- Camichel and Dupin (stoboscopic obs.; hot wire)

—+— DVL (Obs. of powdered surface of liquid)

—++— DVL (aeolian tones)

—·—·— Lehnert (Pitot tube)

----- Resistance coefficient c_W

(h = perpendicular distance between the two lines of vortices and l = distance between successive vortices on the same line). Assuming that at some distance behind the body a stable vortex pattern is maintained and the fluid is at rest at a sufficiently large distance from the body, von Kármán was also able to calculate the resistance using the impulse theorem with the aid of his theoretical findings. With

$$W = c_W \frac{U^2}{2} D$$

(W = resistance per unit length of the body, = density of the fluid, U = flow velocity, D = body diameter or plate width) we get the resistance coefficient

$$c_W = 2\left[0{,}799\frac{u}{U} - 0{,}323\left(\frac{u}{U}\right)^2\right]\frac{l}{D},$$

where $\frac{u}{U}$ (u = velocity of the vortex system) and $\frac{l}{D}$ after von Karman are not computed but found experimentally.

Von Kármán and Rubach found: /478

$$\left(\frac{u}{U}\right)_{plate} = 0.20;$$

$$\left(\frac{u}{U}\right)_{cyl.} = 0.14;$$

$$\left(\frac{l}{D}\right)_{plate} = 5.5;$$

$$\left(\frac{l}{D}\right)_{cyl.} = 4.3$$

Theoretical considerations of Heisenberg [5] give the values

$$\left(\frac{u}{U}\right)_{plate} = 0.229$$

and

$$\left(\frac{l}{D}\right)_{plate} = 5.45$$ [1]

Using the empirical vlues of von Karman and Rubach, Krueger and Lauth [6] , by means of the relationship N · l = U - u

1. But cf. the objections to this of L. Prandtl, Physik. Zeitschr., 23, 366, 1922.

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(N = vortex frequency), have computed the dimensionless frequency $\frac{ND}{U}$ = 0.20 for circular cylinders. This value is in good agreement with the frequency of Strouhal's aeolian tones. Krueger and Lauth have thus shown that aeolian tones are caused by vortex shedding. Later experiments by Krueger [7] on the hydrodynamic interpretation of aeolian tones gave a mean value of $\frac{ND}{U}$ of 0.192. Disregarding the fact that Krueger did not show the frequency to be a function of the Re number, then this $\frac{ND}{U}$ mean value, which /479 is in close agreement with the $\frac{ND}{U}$ value computed by Krueger and Lauth from the von Karman and Rubach measurements, can be viewed as experimental proof that aeolian tones and vortex frequencies are one and the same.

Relf [8] carried out more recent studies along the lines of Strouhal. His whirling arm was coupled directly to the shaft of an electric motor. Relf also studied vortex frequencies on fixed cylinders in a hydrodynamic trough. The frequencies were analyzed by means of a delicate pendulum immersed in the vortex street. In the range of small Reynolds numbers the results are in good agreement with the whirling arm measurements (common mean curve in Fig. 1).

In addition to frequencies, distances between successive vortices and vortex intensities were measured by Thom [9] with the aid of the thin secondary cylinder which was set up about in the middle of the vortex street parallel to the main cylinder. Both cylinders had the same period of oscillation. The dimensionless frequencies, which covered about the same range of Reynolds numbers as Strouhal's aeolian tone frequencies, are on the whole - disregarding considerable dispersion - in good agreement with the latter, except for the end values, whose mean at about Re = 700 has a value of 0.210. As the measurements of other authors show, these last values appear to be completely reliable.

Tyler [10] shows a multitude of ways to determined frequency. Insofar as we are dealing with basically familiar

methods such as observation by means of sprinkling the surface of a liquid with aluminum or lycopodium powder, whirling arm measurements, and hot-wire determination in air and water we will not discuss the experimental setup in more detail. A new method is the analysis of vortex frequency using a fine Pitot tube [11]. It is placed as a probe in the vortex region of the cylinder where the frequency of air pressure variations for a given time at a fixed location, i.e. the frequency with which an individual vortext formation turns up at the dynamic pressure point of the device, is detected and listened to by ear at the other end of the Pitot tube. The measurements, which serve mainly for the determination of critical flow velocities and also for the determination of frequency as a function of the angle of incidence, extend to the lower limit of the frequency range and cover a range of Reynolds numbers from 44.3 to 180. In comparison with Tyler's findings from the methods cited above, the lower portion of the rising branch of our $\frac{ND}{U}$ curve is about 13 to 14 percent higher. Both curves encompass Strouhal's curve up to Re $\sim$ 180 where they almost meet this one. The further path of the Tyler curve from air and water measurements - the air and water measurements are in good agreement, incidentally - is very interesting because there is no steady increase up to a constant value, rather a kind of jump occurs at Re $\sim$ 200 with an $\frac{ND}{U}$ value of 0.18 up to Re $\sim$ 400 (Fig. 1). Only after a new rise from this point on does the $\frac{ND}{U}$ value at Re $\sim$ 1,000 reach its maximum of 0.20 which is maintained up to Re $\sim$ 4,000, the limit of the measurements.

Camichel and Dupin [12] have performed several vortex frequency test series on cylinders over the range of Re numbers from 47 to about 10,000. The lower limit is the critical Reynolds number, found by them, where the vortex street becomes asymmetrical with a $\frac{ND}{U}$ value of 0.117. A constant $\frac{ND}{U}$ value of 0.185 is reached at about Re = 350 and is maintained up to Re = 450, the upper limit of the studies for small Re numbers. The results of the experiments for large Re numbers from 1,000 to 10,000 are distributed around an $\frac{ND}{U}$ value of 0.200. Cor-

relation of the results of both test series in the Re number range 450 to 1,000 is lacking. Besides the hot-wire method the following was used for frequency determination. A sufficiently long white thread was placed in the middle of the vortex street and its oscillations, corresponding to the movement of the liquid, were observed stroboscopically.

The most recent frequency measurements, which were published after the experimental studies of the above work were completed, come from Blenk, Fuchs and Liebers of the DVL [1] [13]. For experiments in a hydrodynamic tank they are in the Re number range 350 to 2,000 and about 3,500 to 30,000 for wind tunnel measurements. The first were obtained by visual observation (counting the number of vortices per unit time) and the second listening to the tones produced.

Lock [14], using the Kármán resistance equation, computes the resistance coefficient for cylinders from the frequencies of Relf [8] and Relf and Simmons [15] and from the distances between successive vortices measured by von Kármán and Rubach. The c_w curve obtained in this way agrees in general with the /480
curve of the experimental c_w values from measurements made by the National Physical Laboratory up to Re = 10^4 and from the Goettingen measurements for higher Re numbers. Numerically, the computed c_w curve lies 14 to 20 percent lower than the curve found experimentally, apart from a small region around Re = 2,000 where the computed curve lies about 4 percent above the experimental curve.

Up to now there exist only a few studies on flat plates and these are basically limited to the investigation of frequency as a function of the angle of incidence. By contrast there is still little evidence to show it as a function of the Reynolds number.

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1. DVL = Deutsche Versuchsanstalt fuer Luftfahrt (German Test Center for Aeronautics).

Fage and Johansen [16], on the basis of only six test points using hot-wire measurements for Reynolds numbers from 32,000 to 180,000 on plates perpendicular to the flow, have arrived at a $\frac{ND}{U}$ constant of 0.146 with a deviation of $\pm$ 1.4 percent. A test series performed to find out the dimensionless frequency as a function of the angle of incidence Θ in the range $90^\circ < \Theta < 12^\circ$ ($= 90^\circ$ indicates perpendicular to the flow) shows an initial slow and then sharp rise in frequency with increasing angle of incidence. From 9° to 0° the authors assume a further rise in $\frac{ND}{U}$. By putting the projection of the plate width on the plane normal to the flow direction ($D \sin\Theta$) in place of D in $\frac{ND}{U}$ they obtained an approximate constant value of 0.148 for the dimensionless frequency in the 90° to 30° angle of incidence range.

For smaller Re numbers Tyler [11] made measurements of the frequency as a function of the angle of incidence. By plotting his four frequency values for plates exposed perpendicular to the flow over Re we see a maximum around Re = 1,500 (Fig. 10). Tyler himself did not plot this, since he was not investigating frequency as a function of the Reynolds number. When the angle of incidence was varied, since $\frac{ND}{U} = f$ (Re) the flow velocity must have remained unchanged, which Tyler, however, did not take into consideration. In particular, for two test series, the Reynolds numbers, with regard to D, for small angles of incidence are Re = 368 and Re = 1008 respectively, and for plates perpendicular to the flow, Re = 1,555 and Re = 2730 respectively. The angle of incidence $\Theta = 0^\circ$ (parallel to the flow) is reached in only one test series, for which the Re number is also to be viewed as more or less constant, with $\frac{ND}{U}$ = 0.970 and 1.09 (Fig. 12).

Studies on plates of vortex frequency as a function of the angle of incidence have also been made in connection with cylinder measurement (see p. 489) at the DVL. The results agree qualitatively with the English findings (Fig. 12). In the figure only the curve is plotted corresponding to the test series in which the angle of incidence 0° was reached. By projecting the

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resistance section on the plane normal to the flow, $F = D \sin \Theta + \delta \cos \Theta$, where D = width of the plate, δ = thickness of the plate and Θ = angle of incidence, the authors got a dimensionless

$$\frac{NF}{U} \quad 0.18$$

nearly independent of the angle of incidence.

3. Purpose of the Present Study

From the above section it can seen that measurements on vortex streets go back a long ways - and in recent times they have been carried out at an increased rate - both in water and in air and with various methods. The results of these studies differ from one another, however, on certain points, sometimes not insignificantly. This is particularly true for smaller Reynolds numbers. It therefore seemed advisable to make further measurements in this region. They cover cylinders held perpendicular and inclined to the flow and plates perpendicular to the flow and at angles of incidence ranging from 0° to 90°. Since the measurements on wires and thin plates were carried out in an air flow where the vortex frequency was in the audible range, it turned out that acoustical methods were readily appropriate.

It was possible when dealing with the cylinders (wires) to use two different acoustical methods simultaneously; namely, listening by means of the Pitot tube (as Tyler did) and resonace tone determination on the resonance points of the wires which was used in the classic study by Strouhal, but since seems to have fallen into the background.

The range of Reynolds numbers for the cylinder studies extends from Re = 50 to 1,350, i.e. they lie for the most part in the region where $\frac{ND}{U}$ rises sharply with increasing Re, /481 however the measurements still extend into the region where the dimensionless frequencies are independent of the Reynolds number. For inclined cylinders only the study by Tyler was available. Therefore new measurements also seem appropriate here.

While in previous measurements of vortex frequency behind plates in a flow the effect of the Reynolds number was not taken into account, this effect was also investigated through our appropriate measurements for various angles of incidence. Besides these frequency measurements, measurements of the distance between seccessive vortices were also now made for the plates by means of a suitable extension of the Pitot tube method. With the aid of the Karman equation both measurements together allow us to compute the resistance coefficient, as Fage and Johansen have already similarly done, but only in the region of a constant resistance coefficient. In order to be able to make the comparison between theory and experiment as accurate as possible, resistance measurements were also made by weighing. In the region of small Reynolds numbers experiments on this score are still not available.[1] These resistance measurements were also expanded to other angles of incidence down to 0° as there was no published test data of any kind for small Re values for this type of measurement.

In measureing the distances between successive vortices behind the plate it turned out that the distance is a function of the distance away from the plate. This, as well as a corresponding dependence of vortex frequency, forms another object of research.

Chapter II: Description of the Experimental Setup

1. The Wind Tunnel

The wind tunnel in its original form has been described by Linke [17]. Consequently we will only deal with it briefly here, taking into consideration the changes which have been made in the meantime.

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1. Shortly before these measurements were completed a study appeared by O. Flachsbart on the resistance of plates which deals with the same region of Re numbers, however it covers only plates exposed perpendicular to the flow.

Fig. 2 shows the built-in installation in the glass-roofed hall of the Physical Institute (35 m long, 10 m high, 15 m wide). A Siemens-Betz screw-type compressor sucks in air from the surrounding space which is forced into a diffuser channel K and comes out as a free jet through the nozzle D. The air stream is made rotation free by means of a vaned diffuser system 55 cm behind the compressor. A straightener and a wire screen in the largest section of the diffuser provide for a straight and nearly homogeneous flow. Velocity differences still existing beyond the straightening section are equalized by the nozzle which has a section ratio of 1:4. Thus fluctuations in kinetic energy of say ±16 percent in the large section are reduced to ±1 percent in the free jet. This corresponds to velocity fluctuations in the free jet of only ±½ percent.[1]

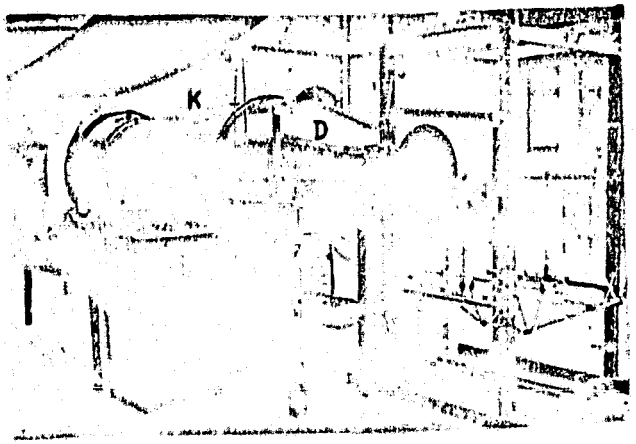

Fig. 2. Free jet apparatus with electrical control device.

As a result of numerous attempts to eliminate wind tunnel noise all pieces of equipment in the immediate vicinity of the intake side of the fan were removed as long as they did not have to remain in place for safety reasons. By removing two vertical bars and the fine mesh protective screen, and mainly by polishing the surfaces of the fan propeller blades to a high sheen[2], we managed, in addition to achieving the desired noise reduction, to achieve a maximum velocity of the air flow of about 20 m/sec for long periods and about 21 m/sec for short periods, which, in comparison with the maximum velocity prior to /482 the changes, corresponds to a velocity increase of about 21 and 27 percent.

1. Cf., for example, B.L. Prandtl, Ergebn. d. Aerodyn. Versuchsanst [Findings of the Aerodynamics Test Center], Goettingen, No. 1, p. 11, 1925.
2. On the suggestions of Mr. Schilhansl.

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2. Electrical Regulation

Since for technical reasons we could not use the Institute's accumulator battery as the energy source, the electrical setup for the wind tunnel had to be fundamentally rearranged. The municipal direct current supply of 220 and 330 volts which we used first required a stabilizing intermediate stage to adequately eliminate temporary fluctuations in voltage whicht amounted to about ±5 percent. For this we chose a set of 20 "Osram" iron ballast tubes connected in parallel (Fig. 3). The entire I-B-T combination including a voltmeter VM connected in parallel to this is in series with the starter A, the box resistor KW, the fine control resistor FW, the Motor M and the ammeter AM. At a current consumption of 1 amp each of the resistance lamps has an average voltage drop of 80 volts and a control range from 40 to 120 volts. By connecting the tubes stepwise in conjunction with the fine control resistor FW any velocity of the free jet in the range from 1 m/sec to 21 m/sec can be set with approximately the same constant which was also produced by the accumulator power supply:

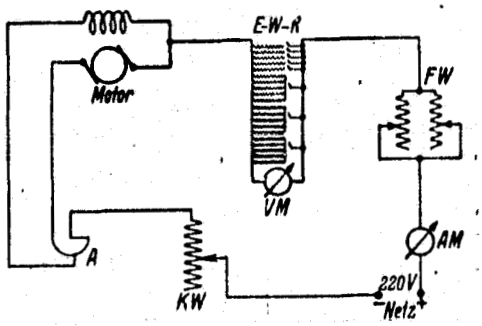

Fig. 3. Wiring diagram of the electrical system of the wind tunnel.

Accumulator: ±0.3 percent,
Mains with I-B-T: ±0.7 percent.

3. The Test Channel

A portion of the frequency measurements (for the cylinders and some of the plates) and the measurement of the distances between successive vortices (for the plates) were made in the free jet.

For the resistance measurements and the frequency measurements on plates perpendicular to the flow the test space was in

a channel 70 cm long of rectangular section measuring 68 x 12 cm. The plywood side walls were firmly mounted to a wooden frame which also held the balance. The roof and floor of the channel were made of cardboard. Connecting the nozzle opening of the wind tunnel and the test space was a cardboard nozzle 50 cm long.

4. The Balance

Determination of the resistance for small Reynolds numbers demanded a very sensitive balance. This condition was met by a two-component balance bases mainly on a design by Burbach which Linke used for his measurements on cylinders (cf. W. Linke [17], Ch. II, 3, Fig. 6 .

The balance was redesigned for our plate measurements. Since the air flow was good and horizontal we did without the equipment for measuring the vertical energy component. The new arrangement is shown in Fig. 4. The plate Pl is held by means of two specially designed holders T, which are described in detail in section 6, between the vertical arms B of the compound lever system which turns around the support points L. By appropriately weighting the balance dishes A the forces on the plate can be equalized. The equilibrium position of the balance can be determined by a pointer Z on scale S fixed to the lever arm.

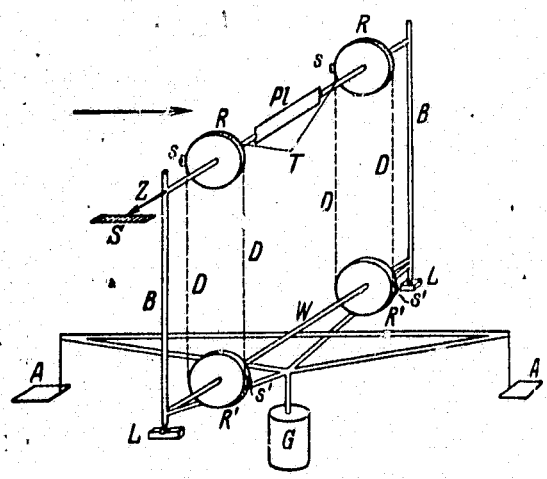

Fig. 4. Schematic diagram of the balance.

The elaborated mounting device raises the center of gravity of the balance so as to endanger its stability. Therefore a weight G, as in Fig. 4, /483 was attached to the balance. By altering the size of the weight and also by moving it up and down the center of gravity of the entire balance system could be changed allowing for the required

sensitivity for each test series to be achieved. It was possible to determine loads of 0.005 g and to interpolate loads of 0.001 g.

An oil damper was used to still the swinging of the balance.

5. Protective Covering for the Balance

In order to prevent additional air forces from affecting the measurements the balance, along with the observation post, was completely covered with packing paper (Fig. 5). The test channel V passed through the protective covering. The protective covering proved to be necessary in the course of the preliminary experiments because the free jet coming out of the test channel caused a movement of the neighboring air masses. For a correction used for measurements without the protective covering see Chapter II, Section 6c.

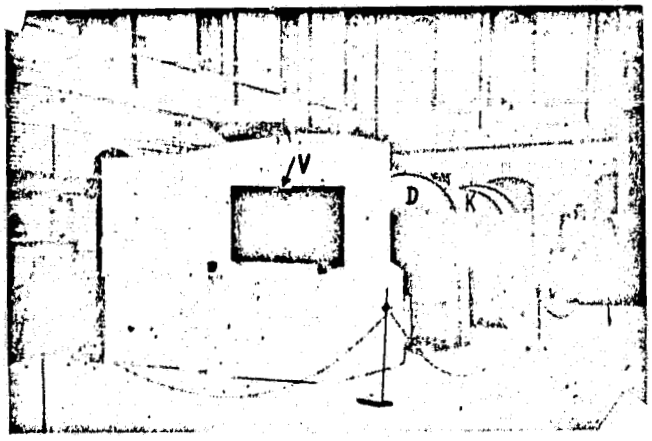

Fig. 5. Overall view of the test setup with the protective covering for the balance.

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6. Mounting the Plates

In order to keep the thin plates from bending or twisting when exposed to the flow the clamping device was specially designed (Fig. 6). A brass H-beam MP is connected to each of the two vertical balance beams B and to a circular ring K into a rigid system. This serves to guide the actual plate holder T which is pressed into the support L by a strong coil spring f. This is sufficiently adjustable so that inaccuracies in the position of

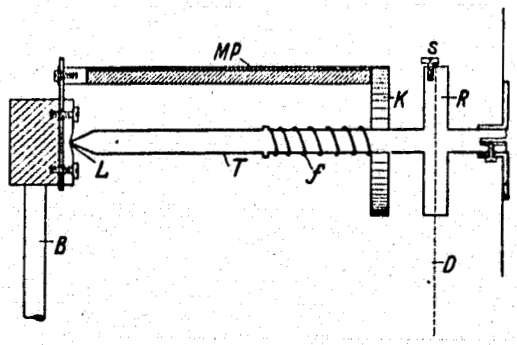

Fig. 6. Mounting device for the plates.

the holder T to the tunnel wall S (through which it passes) which arise during mounting can be compensated for. The mounting of the experimental plate Pl can be seen in Fig. 7 where the passing of the plate holder T through the tunnel wall S is shown in detail (cf. Section 7).

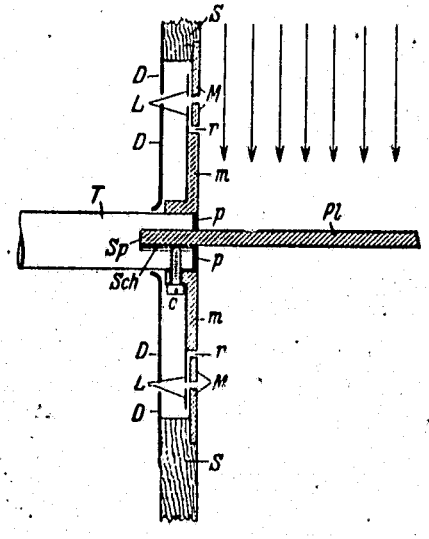

Fig. 7. The passing of the plate holder through the tunnel wall.

Varying the angle of incidence requires an additional device on the support setup which is shown schematically in Fig. 4 (cf. also Fig. 6). In order to prevent twisting of the plate when putting it in place both sides of the mount had to be tightened at the same time. This was done as follows:

A circular brass disc R is soldered to each of the two holders T. Two discs R' the same size as R and lying in the same plane with its partner R form the ends /484 of the shaft W which turns approximately along the axis of rotation of the balance parallel to the length of the test object Pl. R and R' on each side are connected by a loop of tautly strung thin stell wire D. The wire D is fastened to R and R' by means of the screws s and s'. One of the discs R' is fitted with a pointer which indicates changes in the angle of incidence of the test object on a degree scale.

Before the start of the experiment the test plate is fixed to both sides in the holder T (cf. Section 7). The wires D are not yet fastened so that the holders T can be turned independently of one another until the clamped plate is straight. Then the screws s and s' are tightened. The system is now hooked up and by turning one of the holders T or the shaft W the angle of incidence of the test object is changed, corresponding to the amount shown by the pointer attached to R'.

7. Passing the Plate Holders through the Tunnel Walls.

Passing the plate holders through the tunnel walls was modelled on an arrangement used by Linke [17]. The diagram is shown in Fig. 7. Each of the side walls of the tunnel has a circular opening in the middle 20 cm in diameter. This is covered on the inside of the tunnel by a 2-mm thick circular brass disc with a concentric opening in the center 2 cm in diameter. The cylindrical holder T projects into this opening, about 0.2mm back from the inner surface of the tunnel wall. A brass flange is place on the holder which completes the tunnel wall, leaving only a 0.5mm circular slot r for the turning of the balance. To prevent interfering air movements through the circular slot a labrynth packing is made by means of a thing disc of paper L glued to the brass flange m and a pressboard lid D. A flat slot Sp cut into the holder T, whose width could be varied by means of a washer controlled by the screw c, served to clamp the test plates into place. The opening remaining between the test object and the sides of the slot was packed with a paper ring which at the same time was so shaped that it exactly filled the depression where the holder T was recessed in the flange m. In this was we managed to keep the plate completely flat when locking it into place.

8. Mounting the Cylinders and Plates for the Free Jet Experiments

a) Cylinders. Two methods were used to mount the cylinders. In one the cylinder was mounted horizontally, perpendicular to the airflow, about 40 cm from the nozzle in a wooden frame, the structural parts of which lay outside the free jet. By means of two plywood plates (70 by 68 cm) parallel to the flow through the middle of which passed the cylinder and also by covering the parts of the cylinder leading to the outside, it was seen to that only the homogeneous part of the flow 40 cm wide touched the cylinder. The overall length of the test object was 114 cm.

The other method which served for the study of frequency as a function of the angle of incidence used a square wooden frame 20 cm on a side. In this case as well the cylinders were mounted horizontally and could, because of the vertical axis of rotation of the frame, be inclined to the direction of the flow. By means of a pointer attached to the frame the inclination angle could be read off a horizontal degree scale.

Tension regulation for both methods was accomplished as follows:

Both ends of the cylindrical wire were passed through an opening bored in a wooden screw perpendicular to the axis. By turning down on the screw in the wood frame the wire was tightened and now the tension could be varied at will.

b) Plates. Each of the plates - with respect to their vertical dimension - were mounted in the middle of a metal frame. This was rectangular in shape, 40 cm wide and with an adjustable height between and 30 cm. Both the length of the plate and the tension could be so chosen such that, on the one hand, for the narrowest plates by choosing a narrow frame (10 cm high) practically no bending occurred when it was exposed to the flow, and, on the other hand, for the wide plates, by expanding the frame (30 cm high) the middle region of the plate would not be affected. The angle of incidence was changed by turning the frame about an axis of rotation coxial with the object. When studying a small angle of incidence it was possible, after sufficient tightening of the remaining parts of the frame, to remove the vertical bars lying upstream from the test object. The angle /485 of incidence was again read by means of a pointer attached to the frame and a horizontal degree scale.

9. Measurement of Wind Velocity

Wind velocity was measured with a Prandtl Pitot tube connected to a Prandtl micromanometer with a vertical intake tube. With

practice a good reading could be gotten from a 0.01 mm column of alcohol.

10. Correction of the Dynamic Pressure Reading for the Free Jet Measurements

a) For the cylinder measurements. The dynamic pressure was determined at the exit section of the nozzle. During the actual measurements the pressure point of the Prandtl tube still projected about 6 cm into the nozzle. By means of pressure measurements along the axis of the jet we found an increase of 6.6 percent in dynamic pressure from the test site in the plane of the nozzle up to the plane of the cylinder, which was correspondingly taken into account when the results were evaluated.

b) For the plate measurements. The Pitot tube used for determining flow velocity was placed in front of the middle of mounted plate - with its pressure point about 10 cm away - and could, for purposes of getting a reading of the dynamic pressure - be moved along the plate in a given space. During frequency measurements the Pitot tube was removed. To get a reading of dynamic pressure in the plane of the plate the plate was removed and, with the wind velocity kept the same, the Pitot tube put in the place of the removed plate. This was done for all plates and for all flow velocities. It turned out that there was an additional correction for velocity which is a function of the width of the plate and the Reynold's number and was correspondingly taken into account for each. For the widest plate, for example (D = 1.00 cm) at Re = 1,500 this amounts to 12 percent and at Re = 7,000 to 10 percent, and for the narrowest plate (D =0.16cm) at Re = 500 it is 10 percent and at Re = 2,000 7 percent.

Chapter III: Experiments and Results

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1. Vortex Frequencies on Circular Cylinders

Circular cylindrical spring steel wires with diameters of

0.030, 0.050, 0.080, 0.100 and 0.150 cm served as test objects. Diameters were measured with a micrometer.

a) Resonance method. The oscillatory wires mounted perpendicular to the flow in the free jet were studied one after the other. At a certain wind velocity the wire being studied began to vibrate; an aeolian harp-like sound could be heard. As the wind velocity was steadily increased the initially weak sound became more intense and then subsided after passing an intensity maximum. A noticeable change in the frequency of the wire tone could not be detected within the relevant velocity interval. Assuming $\frac{ND}{U}$ = consant N, however, it should change about a semitone, which can be detected by the ear. So we are probably dealing here with a case of interaction (adaptation) between the exciting and exited system (vortex stree and wire).[1]

The pitches were determined by means of a monochord calibrated with a tuning fork. Each tone was assigned to the wind velocity prevailing at its maximum intensity.

b) Pitot tube method. A fine Pitot tube (a hollow steel needle with an inside diameter of 0.08 cm and an outside diameter of 0.11 cm) was placed in the vortex region about 6 diameters away from the cylinder in the direction of the flow. The vortex tone which was picked up was carried to the ear through a rubber tube. The frequency of the tone which was heard was determined by means of a monochord. Just as in Tyler [11] a mutual overlapping of the individual patterns of the two vortex rows could be detected, recognizalbe by a frequency jump to the next higher octave when the probe was passed across the middle of the vortex street.

c) Discussion of the vortex frequency measurement on cylinders perpendicular to the flow. The sound frequencies

1. Cf. Helmholtz, Die Lehre von den Tonempfindungen [The Theory of Tone Perception] p. 67; Rayleigh, Theorie des Schalles [Theory of Sound], p. 63.

obtained by both methods are plotted in Fig. 8 in the dimensionless form $\frac{ND}{U}$ as a function of the Re number $\frac{UD}{\nu}$. The individually

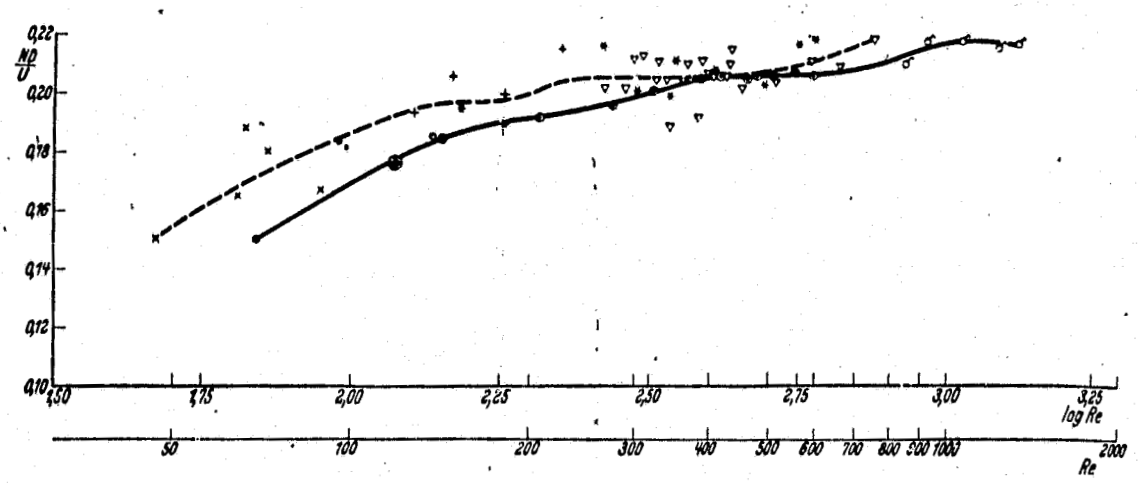

Fig. 8. Vortex frequencies on cylinders perpendicular to the flow.

× 0,03 cm
+ 0,05 cm
* 0,08 cm
▽ 0,10 cm
diameter
Resonance method

• 0,05 cm
⊙ 0,10 cm
σ 0,15 cm
diamter
Pitot tube method

plotted mean curves for the resonance points and the Pitot tube points follow qualitatively the same path but, with the exception of the Re region Re = 350 to Re = 550 in which $\frac{ND}{U}$ is nearly constant, they differ from one another up to 13 percent. Ob- /486 viously the vortex shedding is influneced by the vibrating cylinder. In addition, the results of the two methods used by Strouhal 1 (Fig. 1) give an indication of the same effect; namely, the frequencies found in the region where $\frac{ND}{U}$ is increasing with resonance - hence on the vibrating cylinder - are higher than the frequencies of the pure aeolian tones (non resonant tones).

The effect on vortex shedding (more properly: on $\frac{ND}{U}$) caused

by the vibration of the cylinder may be due to the fact that within the period of one vibration - even as a result of this vibration - different flow velocities arise. This assumption is suggested by the fact that the above mentioned discrepancy occurs precisely in the regions of Reynolds numbers in which $\frac{ND}{U}$ is predominantly dependent on U or Re, while in the region where $\frac{ND}{U}$ is constant, i.e. in the region where U or Re have no effect, the discrepancy also disappears.

Our Pitot tube measurements are in good agreement with Tyler's Pitot tube measurements [11]. The mean curve of our $\frac{ND}{U}$ values begins at Re = 72 with $\frac{ND}{U}$ = 0.15, at first rises sharply up to Re = 175, has four inflection points further along its path at Re = 215, 320, 500 and 840 with corresponding $\frac{ND}{U}$ values of 0.192, 0.199, 0.205 and 0.211, and at about Re = 1125 it reaches the $\frac{ND}{U}$ value of 0.216. In general, the path of the curve corresponds to the frequency curve obtained by other earlier methods of Thler [10], but the rising section is about 8.7 percent higher, and the maximum about 4.4 percent higher (cf. the mean curves in Fig. 1).

An analogous curve path is shown by a mean curve plotted by us using Thom's frequency values (Fig. 1). Its rise between logRe = 1.4 and logRe = 2.2 coincides with the Tyler rise, but in contrast its dip at logRe = 2.4 is about 6 percent lower. A steeper rise then at logRe = 2.7 leads to the maximum, with an $\frac{ND}{U}$ value of 0.212, almost reaching the greatest value of the Leipzig measurements.

A test series by Relf and Ower which we take from the graph by Thom [9] (cf. Fig. 7 in Thom's work) likewise shows a dip at the same Reynolds number with the same frequency value, but at about logRe = 2.0 it lies about 19 percent lower and at logRe = 2.8, 7.5 percent lower than the curve obtained by us from the Thom values.

If a mean curve is plotted using Strouhal's frequency

values (Fig. 1) a weak maximum at log Re = 3.25 is also recognizable here after a maximum constant value has apparently been reached.

The compensation curve for the DVL measurements [13] [487] is in good agreement with the Leipzig measurements for high Re numbers.

In summary we can say that from the measurements of different authors the dependence of the dimensionless frequency on the Reynolds number in the range Re = 25 to Re = 30,000 is roughly established. The frequency curve rises from $\frac{ND}{U} = 0.085$ at Re = 25; at Re = 215 and Re = 320 it shows an inflection point; and after passing a maximum at Re 1,300 up to 2,000 there is a gradual decline in frequency. This curve nearly mirrors the resistance curve which in the region of Re = 120 and Re = 500 has an inflection point and at Re 2,000 has a maximum. The mean curves of the individual authors are plotted together with c_w over Re. Critical areas of the cylinder flow must surely be assigned to the inflection points. In this sense then certain differences between the results of the individual authors are also explained by the difference in the degree of turbulence of the flow which we know from experience always affects the flow in the vicinity of critical numbers.

2. Vortex Frequencies on Cylinders Inclined to the Flow

In addition, vortex frequency as a function of the angle of incidence was studied using the resonance and Pitot tube methods. In each case the wind velocity was held constant and the anle of incidence varied. For a relatively small angle of incidence resonance tones were obtained, but Pitot tube tones were always obtained.

The dimensionless frequencies plotted against the Reynolds number in Fig. 9 with the angle of incidence θ being varied

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yields four more or less parallel curves. (In order to make the graph more clear only the points for = 90°, 60°, 45°, 30° were plotted, in which 90° means perpendicular to the flow and 0° parallel to it. For = 90° and 30° separate curves are plotted from the resonance and Pitot tube findings.) According to this, inclining the cylinder against the direction of the flow causes a shift of the frequency curve towards smaller values. The same behavior is shown by the curves plotted from Tyler's measurements [11] for the same angles, but the disperion of the angle of incidence points is smaller here than in our findings. It can be seen from the figure that as the angle of incidence decreases the Pitot tube tones gradually become higher than the resonance tones.

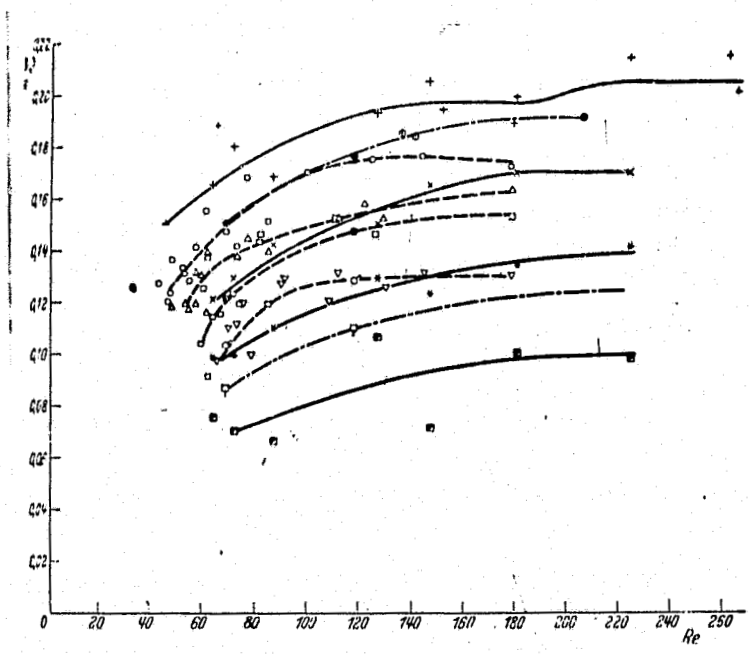

Fig. 9. Vortex frequencies on inclined cylinders.

◦ Θ=90° ▲ Θ=60° ▫ Θ=45° ▾ Θ=30° Pitot tube (Tyler)

+ Θ=90° × Θ=60° * Θ=45° • Θ=30° Resonance (Lehnert)

• Θ=90° • Θ=60° ▫ Θ=45° ▿ Θ=30° Pitot tube (Hehnert)

Mean curves: — — — Tyler (Pitot tube). ——— Lehnert (Resonance and Pitot tube). —·— Lehnert (Pitot tube).

3. Vortex Frequencies on Plates

Extruded brass bands served as test objects for all the plate measurements. The surfaces were well polished, the corners carefully sharpened and free of burrs. Some of the plates were measured with a micrometer (preliminary experiments) and some with a comparator (main experiments).

a) Perpendicular to the flow. Vortex frequencies were determined at a distance of 6 plate widths from the test object by means of a fine Pitot tube as in the cylinder measurements (cf. III, 1b). In the first series of experiments in the free jet the plates were mounted in a frame (cf. II, 8b). In the middle of the plate where the frequency was measured a flat flow /488
could be assumed. For accurate determination of the plate position when it was perpendicular to the flow, the measurement was done in such a way that the plate was continually turned and measuring points were taken at about every degree. In plotting the results we get a curve whose extreme is the value for the plate held perpendicular to the flow.

After preliminary experiments in the free jet - with 16 plates ranging in width from 0.16 cm to 1.00 cm - had resulted in no definite determination of the frequency curve,[1] frequency measurements for plate perpendicular to the flow were made in a closed tunnel where some of them were made at the same time as the weighing of the resistance (see below) and some immediately afterwards. In addition, 3 plates were used, one of which - 0.538 cm wide - was made trapezoid shaped by sharpening the corners (isosceles trapezoid 0.0996 cm high and 45°-angles at the base) while the other two (0.787 cm wide and 0.395 cm wide) were rectangular with a 1:8 (thickness:width) ratio. The results obtained using these test objects (Fig. 10a) show hardly any more dispersion, which is surely due to the fact that the

1. Apparently the position of the maximum at Re = 1,500 (see below) was very sensitive to outside interference to the free jet.

much improved flow - owing to the effect of the cardboard nozzle inserted into the tunnel - is not exposed to any outside influences. Each individual point is the average of at least ten separate measurements. Fig. 10 show in dimensionless form the thus obtained $\frac{ND}{U}$ values as a function of Re. A sharp rise from $\frac{ND}{U} = 0.135$ at Re 600 extending up to the maximum $\frac{ND}{U} = 0.157$ at Re = 1,500 is followed by an initially strong then weaker decline until at Re = 4,000 a constant $\frac{ND}{U}$ value is reached.

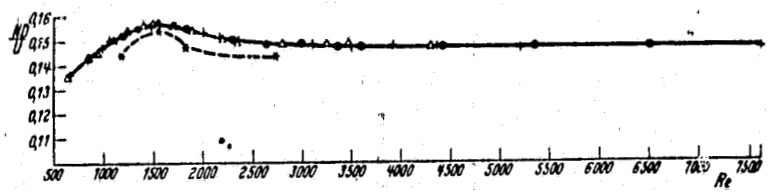

Fig. 10a. Vortex frequencies on plates perpendicular to the flow in a wind tunnel (about 6 plate widths behind the plate).
+ Trapezoid plate D = 0.528 cm
Δ Rectangular plate D = 0.395 cm
⊙ Rectangular plate D = 0.787 cm
* Tyler[1]

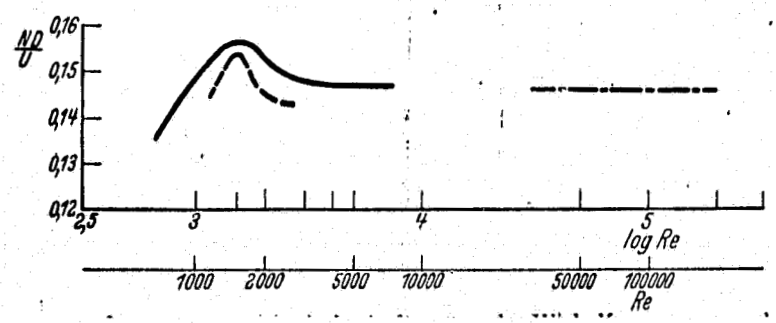

Fig. 10b. Semilogarithmic plotting of vortex frequencies on plates perpendicular to the flow (mean curves).
— — — Tyler. — · — · — Fage and Johansen. ——— Lehnert.

A comparison with Tyler's results 10 which lie in the vicinity of the frequency maximum shows qualitative agreement.[2] His measuring points lie about 2 - 5 percent lower than ours.

1. Cf. the remark about this, p. 480 and the footnote p. 488.
2. Tyler did not perceive this curve since he probably did not suspect any dependence on Re and therefore also did not investigate it.

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Since the dimensionless frequency from Re = 4,000 on is nearly the same (0.7 percent deviation as that of Fage and Johansen [16] in the Re number region 32,000-180,000, it is assumed that there is also constancy in the intervening Re region (7,500-32,000) so that therefroe the dependence of frequency on the Reyondolds number from small values up to 180,000 is known. Concerning the analogy with the c_w-curve cf. Section 6b.

b) Vortex frequency as a function of the angle of incidence. Vcrtex frequency as a function of the angloe of incidence was studied in several test series for plates of varying widths[1] (D = 0.290, 0.343, 0.750 cm) but of nearly the same thickness: width ratio of the section (1:8) in the region Re = 700 to Re = 6,000.

The experiments took place in the free jet. In order to insure a good reading of the flow direction the following method was used. The measurement began with any decired angle of incidence. As the flow velocity was held unchanges the angle of incidence was then varied in steps of 5° or less. The dimensionless frequencies plotted as a function of the angle of in- /489
cidence show, for an angle change over 130°, a curve with a maximum and a minimum. The maximum corresponds to an angle of incidence of 0° and the minimum to the position perpendicular to the flow (θ = 90°). (Cf. Fig. 11, the example for Re = 4882).

For the sake of clarity in the range of the larger angles of incidence all of the measuring points of the individual test series could not be plotted in Fig. 12 since they were often close together. Consequently from the series of experiments only those results of the test series were plotted in which the zero degree position was reached.

The test points for the various Re numbers for angles of 90° - 30° yield a curve with a maximum deviation of ±5 percent around the mean value including the findings of Tyler [10], Fage and Johansen [16] and of the DVL [13]. For smaller angles

1. In order to remain consistent with the designation of the plates placed perpendicular to the flow we here use the word "width" instead of "depth" which is commonly used in aerodynamics.

of incidence frequency is clearly a function of the Re number.

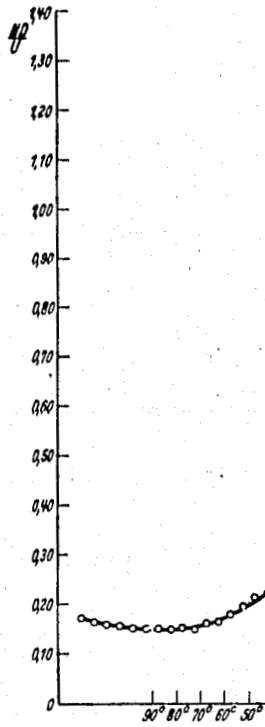

Fig. 11. Determination of the angle of incidence Θ . (Platewidth = 0.75 cm. Re = 4882.)

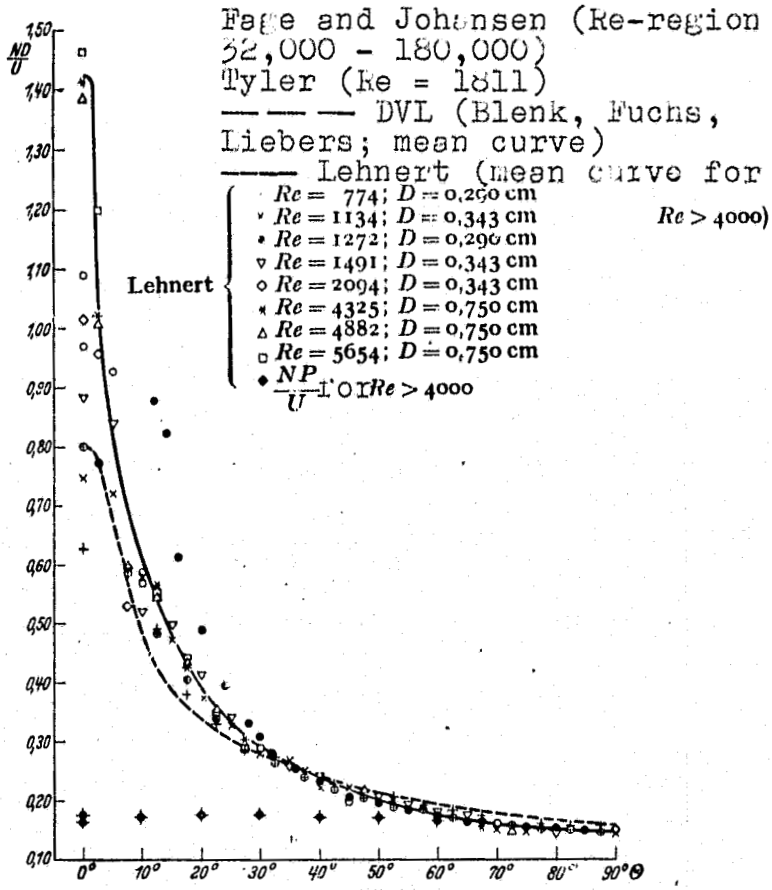
Fage and Johansen (Re-region 32,000 - 180,000)
Tyler (Re = 1811)
DVL (Blenk, Fuchs, Liebers; mean curve)
Lehnert (mean curve for Re > 4000)
Lehnert
Re = 774; D = 0,250 cm
Re = 1134; D = 0,343 cm
Re = 1272; D = 0,296 cm
Re = 1491; D = 0,343 cm
Re = 2094; D = 0,343 cm
Re = 4325; D = 0,750 cm
Re = 4882; D = 0,750 cm
Re = 5654; D = 0,750 cm
ND/U for Re > 4000

Fig. 12. Vortex frequencies on plates as a function of the angle of incidence Θ .

This can be seen in Fig. 13. After an uneventful rise a constant value of $\frac{ND}{U}$ = 1.40 is apparently reached at Re = 5,000 to 6,000. The two values measured by Tyler for $\Theta = 0^{\circ}$ are in good agreement with the curve. The findings of Fage and Johansen and those of the DVL unfortunately cannot be discussed in this respect since in the first place the frequency maximum is lacking altogether and secondly no Re numbers are assigned. If we look at the curves in Fig. 13 which are assigned to the angles of incidence 90°-10° we recognize a similar behavior in the Re number region 1,000 to 6,000, as an overall impression for the group of curves, as was found for the frequency curve for

plates placed perpendicular to the flow in the tunnel[1] (cf. Fig. 10 and Ch. III, 3a, p. 488).

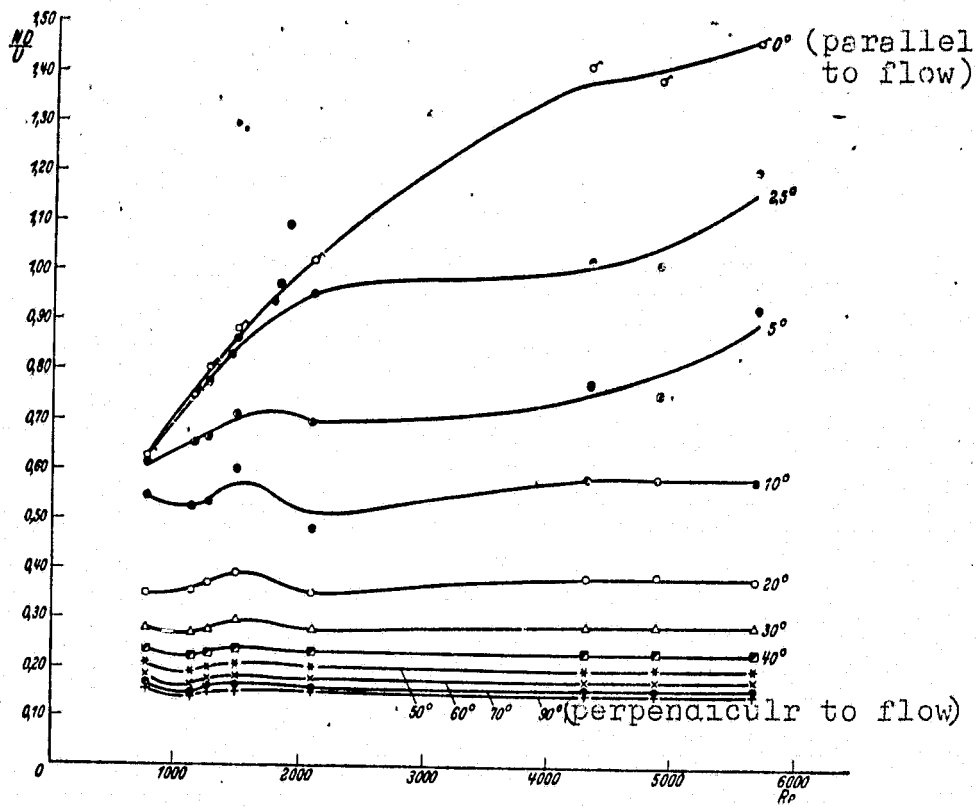

Fig. 13. Vortex frequencies on plates as a function of Re for different angles of incidence Θ in the free jet. •Tyler for $\Theta = 0^{\circ}$.

If, after Blenk, Fuchs and Liebers, we use the form $\frac{NP}{U}$ for the dimensionless vortex frequency in place of $\frac{ND}{U}$ whereby

$$P = D\sin\Theta + \partial\cos\Theta$$

(∂ = plate thickness) is the projection of the section on the plane normal to the flow direction, we get for all Re numbers less than 4,000[2] a nearly constant value of /490

$$\frac{NP}{U} = 0.165$$

with a maximum deviation of $\pm$ 8.5 percent (Fig. 12).

1. If we disregard the decline near Re < 1,000.
2. For Re < 4,000 $\frac{NP}{U}$ for $\Theta < 10^{\circ}$ appears to be a function of Re.

In the same way Blenk, Fuchs and Liebers (VDI) got for $\frac{NP}{U}$ the value 0.18; Fage and Johansen, ignoring the plate thickness (trapezoid shaped plate with sharp corners) got 0.148 for values of θ between 90° and 30°.

4. Distances between Successive Vortices on the Plates

In the plate measurements the Pitot tube method was also further developed to measure the distances between successive vortices as well as the vortex frequencies. For this we used an arrangement of two identical Pitot tubes. Fig. 14 shows a sketch of the experimental setup. The length of the plate runs perpendicular to the plane of the drawing (z-direction). The flow itself gives us the x-direction. The angle tube 1 is brought near the vortex street at an appropriate distance x (about 6 plate widths) behind the plate from the side until at a suitable distance y from the x-axis a frequency tone is audible. Tube 1 is fixed in this position. The adjustment of angle tube 2 occurs in the same way, but it is moved towards the furst tube primarily only along the z-axis in order to avoid any mutual interaction. The other ends of both analysers are connected to rubber tubes which meet at a Y-junction and a tube from this then carries the sound to the ear. Now, for example, if tube 2 is moved along the x-axis, clearly perceivable maxima of tone intensity arise if the Pitot tube openings are at places where phase of the vortex is the same; minima are perceivable when they are at places where the phase is shifted by π. In the first case the interval between the Pitot tubes is one entire multiple of the wavelength, in the second case an odd multiple of half a wavelength. When tube 1 is hled in a fixed position the distance tube 2 must be moved to go from one maximum, or minimum, to the next, is therefore precisely the wavelength

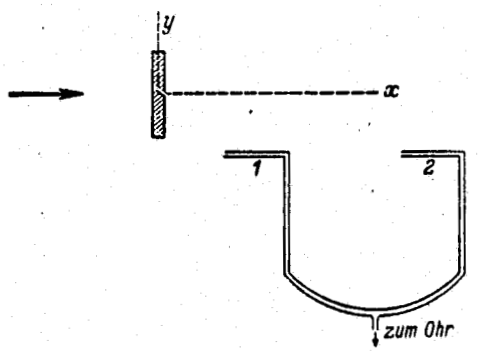

Fig. 14. Combination of two Pitot tubes to measure wavelength.

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we are looking for, or precisely equal to the distance between successive vortices.

Moving the Pitot tubes in relation to one another is made possible by a support off which at the same time can be read in millimeters the amount of movement in the x and y directions.

For determining the distance between successive vortices in the range of small Reynolds numbers this arrangement does not work because the tone intensities are too small. Therefore in place of the subjective method of maxima and minima determination by the human ear and objective method was used. The angle tube arrangement remains unchanged. The conduction tube leading from it is securely attached to an ordinary carbon microphone by means of a special connecting piece in the form of a very shallow funnel (Fig. 15). The modulated microphone current was connected via a three-stage amplifier to a recording device in which, corresponding to the change in energy of the tone when Pitot tube 2 was moved, pointer deflections indicated clear maxima and minima even when the volumes were very low. Specail care was required to shield to microphone against outside electrical and acoustical interference. High frequency electrical effects which showed up in the beginning were suppressed by means of a grounded shielding of the microphone and its leads, while the spring-suspended mounting of the microphone in wadded padding and boxes packed inside one another eliminated any acoustical interference.

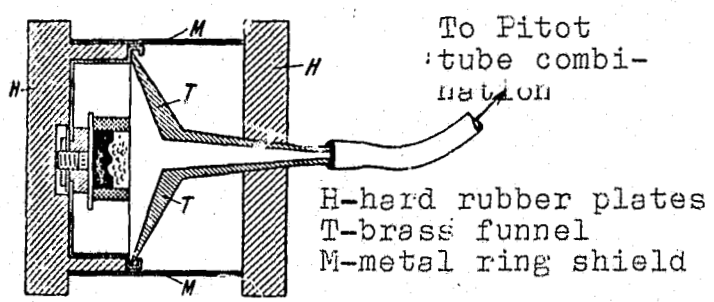

Fig. 15. Microphone for detecting vortex frequencies.

The results are presented in the dimensionless form $\frac{L}{D}$ (L = distance between successive vortices, D = plate width) as a function of the Re number in Fig. 16. The $\frac{L}{D}$ values first decline with increasing Re, there is a minimum at Re $\sim$ 1,800,

then after a slight rise a constant end value for $\frac{L}{D}$ of 5.4 is reached, perhaps following a weak maximum.[1]

5. The Behavior of Vortex Frequencies and Distances between Successive Vortices Close to the Plates

a) Vortex frequencies. When the experiments described in the preceding section were also carried out close to the cylinders and plates (i.e. closer than 6 plate widths) there were significant differences in the results for the two kinds of test objects.

If the Pitot tube is brought close to a plate, starting from a distance of about 6 platewidths away, the pitch level initially remains constant until about one platewidth away, corresponding to a regular vortex frequency (cf. the measurements of N described in the preceding section, designated below as N_2). As we get closer to the plate higher tones are superimposed /492 over this lower tone. They gradually suppress the lower tone and as the distance from the plate decreases the frequency rises still more. The lowest of these higher frequencies, which appears at a distance of about 0.5 D away, is designated at N_1. In corresponding experiments on the cylinder this phenomenon did not occur.

For quantative determinations the frequency as a function of the distance from the plate for Reynolds numbers between 500 and 5,000 was measured with a Pitot tube probe of the same size as in the earlier measurements. Since expecially in close to the plate there was the danger of influencing the vortex shedding by the presence of the probe, comparative experiments with probes many times larger were carried out. These experiments produced no variations in the results beyond the order of magnitude of the test accuracy. We measured the above defined frequency N_1 close to the plate and the frequency N_2 about 6 platewidths away

1. This curve can be distinguished more clearly by focusing on the points for an individual plate.

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from the plate. The ratio $\frac{N_1}{N_2}$, apart from a slight decline below Re = 1,000, is futhermore good and constant at 2.5 (Fig. 17).

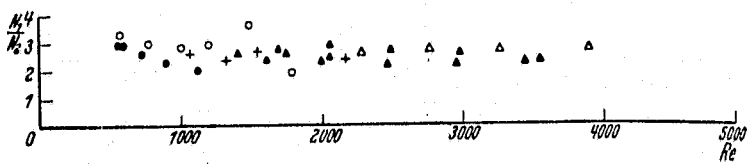

Fig. 17. Ratio of the frequency N_1 close to the plate to the frequency N_2 about 6 platewidths away.

• $D = 0{,}270$ cm
° $D = 0{,}343$ cm
+ $D = 0{,}400$ cm
▲ $D = 0{,}600$ cm
△ $D = 0{,}750$ cm

These results can perhaps be interpreted as follows. The disontinuity surfaces extending from the two corners of the plate roll themselves up in the immediate vicinity of the plate into high frequency vortices (high pitches). Then (at a greater distance from the plate) these small vortices come together to form low frequency larger vortices (lower pitch): Karman vortex streets. The drop in pitch level for the high tones close to the plate can be interpreted in a similar fashion.

In the experiments on the cylinder, as already mentioned, the rise in pitch when the Pitot tube was brought close to the cylinder did not take place. We must then assume that in the case of the cylinder a corresponding assimilation of small vortices does not occur. This finding shows a certain parallel with the results of experiments on the tube intake[1] where for sharp-corner intakes vortex assimilations were detected while they were not observed for intakes which had been rounded off.

b) Distance between successive vortices. The measurement of the distance between vortices did not work with the Pitot tube

1. Cf. H. Kurzweg, Neue Untersuchungen ueber die Entstehung der turbulent Rohrstroemung New Investigations of the Production of Turbulent Tube Flow , Ann. d. Phys. 18, 193, 1933.

combination in close to the plate. So in this case some flow readings were made. The flow apparatus used, designed for demonstration purposes by Dr. Naumann, has the following specifications: the rectangular trough (30 x 45 cm) permits a water depth of about 3 cm. In the middle of the trough, parallel to its length, is the 10 cm wide and 28 cm long test space. The water was kept circulating by two impellers with vertical axes. Two rectangular plates, 1.99 cm and 1.00 cm wide and 0.199 and 0.100 cm thick, served as the test objects. The flow pattern was made visible by sprinkling the surface of the liquid with aluminum powder and was photographed with a 10 x 15 Bergheil camera. The velocity of the flow was determined with the plate removed from the time it took for a small piece of paper or aluminum in the liquid to cover a distance of 20 cm. Since this time varies ±10 percent only qualitative significance can be attached to these measurements. Just the same, the observation of the flow which was made in the range of Reynolds numbers 700 - 2,600 confirms the existence of the higher vortex frequency detected with the Pitot tube in the vicinity of the plate and of the lower frequency farther away from the plate. Up to about 4 platewidths away vortex assimilations are observed[1], thus supporting the interpretation given in section 5a of this chapter. Evaluation of the flow photographs (cf. Fig. 19 as an example) gives the distance betwee vortices $\frac{l}{D}$ as a function of the distance $\frac{\partial}{D}$ from the plate.(Fig. 20). As $\frac{\partial}{D}$ gets smaller $\frac{l}{D}$ also gets smaller, hence its behavior is opposite to the vortex frequency. /493 The value obtained in the Re number region observed for the ratio of the distance between vortices

Fig. 18. ↑ Example of a flow photograph with vortex assimilation.

1. In Fig. 18 ↑ points to such an assimilation process.

near the plate (l) and of that about 6 platewidths away (L) shows considerable deviation. $\frac{L}{l} = 5$ can be given as the mean value, more or less, of our measurements.

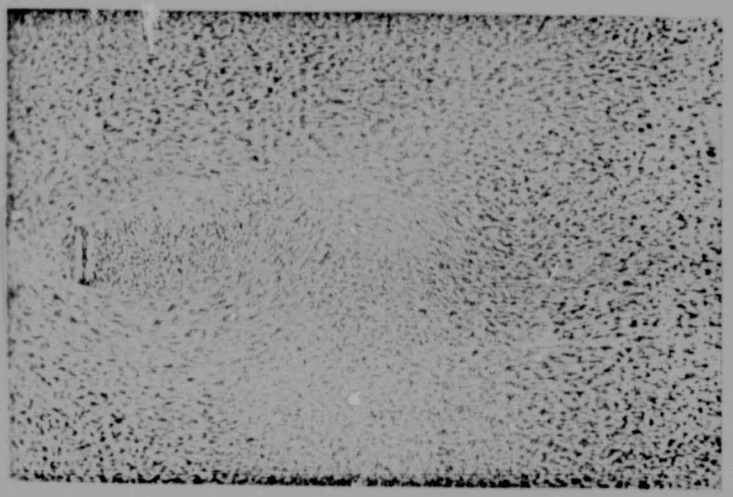

Fig. 19. Example of a flow photograph with small and large distances between vortices.

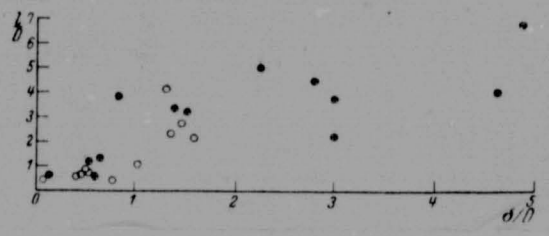

Fig. 20. Distance between vortices l/D as a function of the distance ∂/D from the plate.

⊕ D = 1.00 cm; o D = 1.99 cm

6. Resistance Measurements on Plates

Correction for the influence of the wall. We get the resistance coefficient c_W from

$$c_W = \frac{W}{DB\frac{\varrho}{2}U^2},$$

where D = plate width, B = tunnel width, W = the measured resistance and U = flow velocity in the middle of the tunnel. As a result of the drop in velocity in the boundary layer at the tunnel walls the measured resistance must be corrected. We die this in the following manner. The velocity distribution along the plate (with the plate removed) between the two boundaries formed by the tunnel walls is measured with a fine Pitot tube. The resistance of the middle portion in the homogeneous flow is

$$W_* = W - W_{Gr},$$

when W_{Gr} is the resistance component of the part of the plate lying in the boundary layer. The resistance coefficient curve obtained without the correction is first used as a basis for the calculation of W_{Gr}. The boundary layer is partitioned into n = 8 intervals. For each interval the resistance $W_n = c_{W_n}\frac{\varrho U_n^2}{2}F_n$

is found (c_W is taken from the uncorrected c_W-curve for the mean Reynolds number prevailing in the relevant bounday layer interval). Then $W_{Gr} = 2\sum W_n$ and the resistance W_{*1} on the width of the plate in the homogeneous flow is $W - W_{Gr}$; hence we get

$$c_{W1} = \frac{W_{*1}}{\frac{\varrho U^2}{2} F_*}$$

where F_* = plate width x (tunnel width minus the thickness of the boundary layer. The process is repeated, whereby the c_{W*1} curve is used as a basis for the calculation of the resistance in the boundary layers. In practice the second approximation is sufficient. The correction computation was done for eight partitioned c_W values over the entire test range. The correction resulted in an increase in the resistance coefficient varying between 4.8 and 3.6 percent. Since it was not here a question of a systematic operation with the the Reynolds number a mean correction of +4.2 percent was used uniformly. /494

b) Resistance of plates perpendicular to the flow. For the measurements with which vortex frequency determinations were combined 3 plates were used whose dimensions are given in section 2a, p. 488. Mounting the plates in the turning mechanism of the balance (cf. Ch. II, sections 6 and 7) must be done with special care, since preliminary tests had shown that twisting of the plates caused incorrect readings. It was therefore necessary for each plate to be in very flat alignment.

The c_W-curve obtained is in good agreement with the values of other authors with c_W = 1.97 over the constant region (from Re > 5,000) (Goetingen measurements: Wieselsberger, Flachsbart with c_W 2.0; Fig. 21). Below Re = 5,000 c_W declines, slowy at first, with decreasing Re, then falls off sharply, reaches a minimum at Re 1,500 with c_W = 1.72, and then rises steadily to the value c_W = 2.00 at Re = 6,000.

When we had finished our measurements O. Flachsbart [18]

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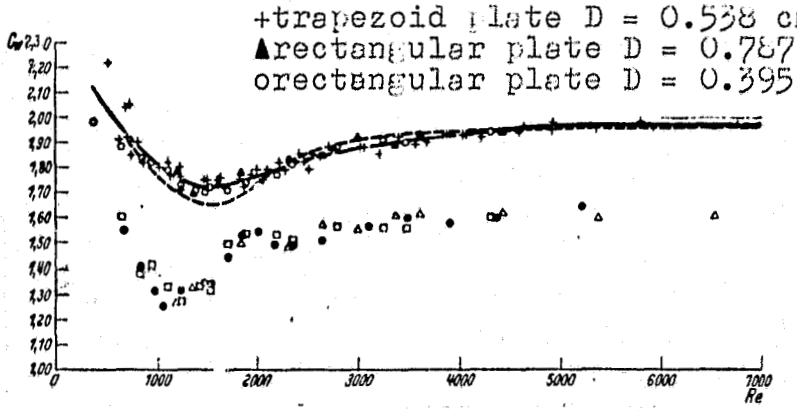

Fig. 21. Resistance coefficient c_w of plates perpendicular to the flow.

•with frequencies on the trapezoid plate
Δwith frequencies on the rectangular plate D = 0.787 cm
owith frequencies on the rectangular plate D = 0.395
(calculated from measured vortex frequencies and distances between vortices using the Karman equation)
— — — Flachsbart (measured, mean curve)
— · — · — Mean curve of the older Goetingen measurements (Wieselsberger Flachsbart).

publis ed a new study on resistance measurements on plates placed perpendicular to the flow in the same range of Reynolds numbers. Our measurements are basically in good agreement with Flachsbart's findings but show only about half as much deviation (Flachsbart: ±4 percent, Lehnert: ±2 percent deviation around the mean value). In the resistance minimum at Re = 1,500 our c_w value is about 4 percent higher. A more gradual rise of our curve leads to an intersection of the two curves at Re = 2,200 and to a maximum deviation downward at Re = 2,700 of 2 percent. In the constant region our measurements are about ½ percent above the more recent measurements of Flachsbart. The deviations in the minimum range can be viewed as a result of various degrees of turbulence of the wind tunnels which have a particularly strong effect precisely in the critical areas. The area around the minumum is surely to be viewed as such.

By comparing the c_w-curve (Fig. 21) with the $\frac{ND}{U}$-curve (Fig. 10) for plates perpendicular to the flow we see a precisely mirror-image behavior. A decline in c_w in the Re range 600-1,500

corresponds to a rise in $\frac{ND}{U}$. After c_w reaches a minimum and $\frac{ND}{U}$ a maximum at Re = 1,500 there follows an initial stronger, then more gradual rise in c_w and decline in $\frac{ND}{U}$ until at Re = 4,000 to 5,000 both curves reach their constant end value.

c) Resistance of plates as a function of the angle of incidence. Resistance as a function of the angle of incidence was studied on 4 plates with widths of 0.395, 0.789, 0.270 and 0.343 cm and with a side ratio of the rectangular section of about 1:8.

The determination of the angle of incidence was again done as in the frequency measurements (see pp. 488 and 489). The resistance maximum corresponded to the position of the plate placed perpendicular to the flow ($\Theta = 90^\circ$), and the minimum to the position parallel to the flow ($\Theta = 0^\circ$).

Since in these tests series, carried out earlier, the balance had not yet been shielded (cf. Ch. II, 5), air currents affected the balance dishes and rods and indeed this brought about a reduction of the resistance of the plate in comparison with the /495
correct value (hence the interfering forces are not due directly to the air jet but to outside interences). This requires a correction. To get it we start with an angle of incidence of 90° (maximum value of the W- Θ -curve) for which we take the correct resistance value from Part III, 6b. The difference between this value and the above value influenced by extraneous air currents affecting the balance was assumed to be valid for each flow velocity determined independent of the angle of incidence. Consequently it was also considered as the additive correction for all other angles of incidence. The relevant amounts of correction for the c_w values rise between 2 and 13 percent for plates perpendicular to the flow with increasing velocity, and for the smaller c_w of the small angles of incidence they are correspondingly greater. The c_w of the smallest angles of incidence will therefore have to be estimated with a certain amount of caution.

In Fig. 22 the results are plotted as a function of the angle of incidence for different Reynolds numbers. If we plot c_w as a function of the Reynolds numbers for different angles of incidence (Fig. 23) all the curves show the same characteristics of the c_w-curve for a plate perpendicular to the flow: first a decline to a minimum at Re = 1,500[1], then a rise turning into a constant value at about Re = 5,000. On the whole there is also for the different angles of incidence from Re = 1,000 upwards an equally analogous mirror-image path of the c_w and $\frac{ND}{U}$ curves as for plates placed 90° to the flow.

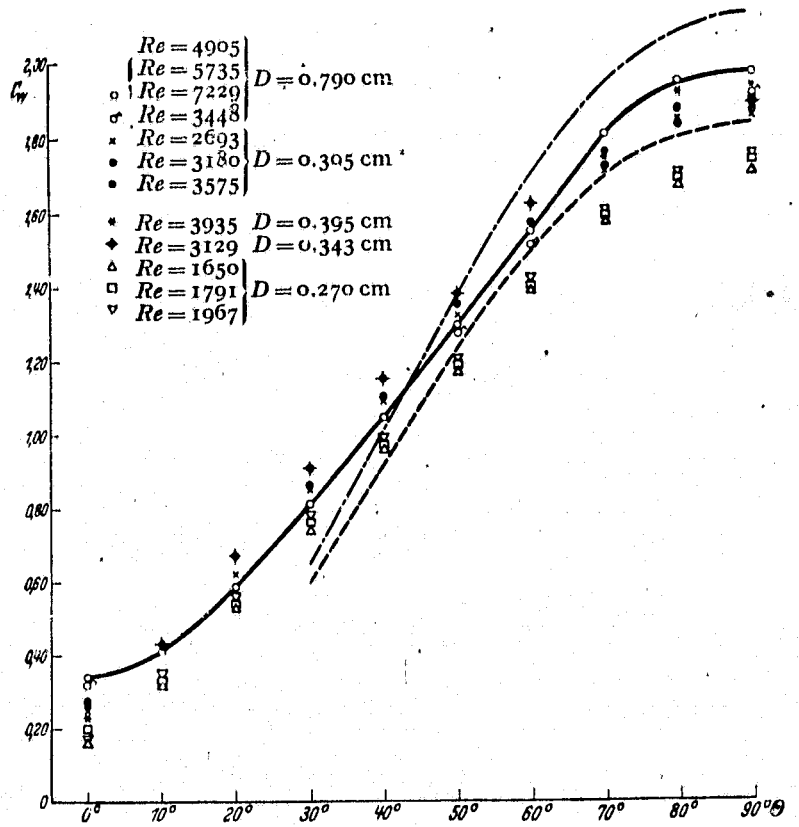

Fig. 22. Resistance coefficient as a function of the angle of incidence for plates.

———— Fage and Johansen (without correction)

— — — Fage and Johansen (with correction cf. footnote, p. 495)

1. The relevant points for the smallest Reynolds numbers are left out in Fig. 22 for the sake of clarity.

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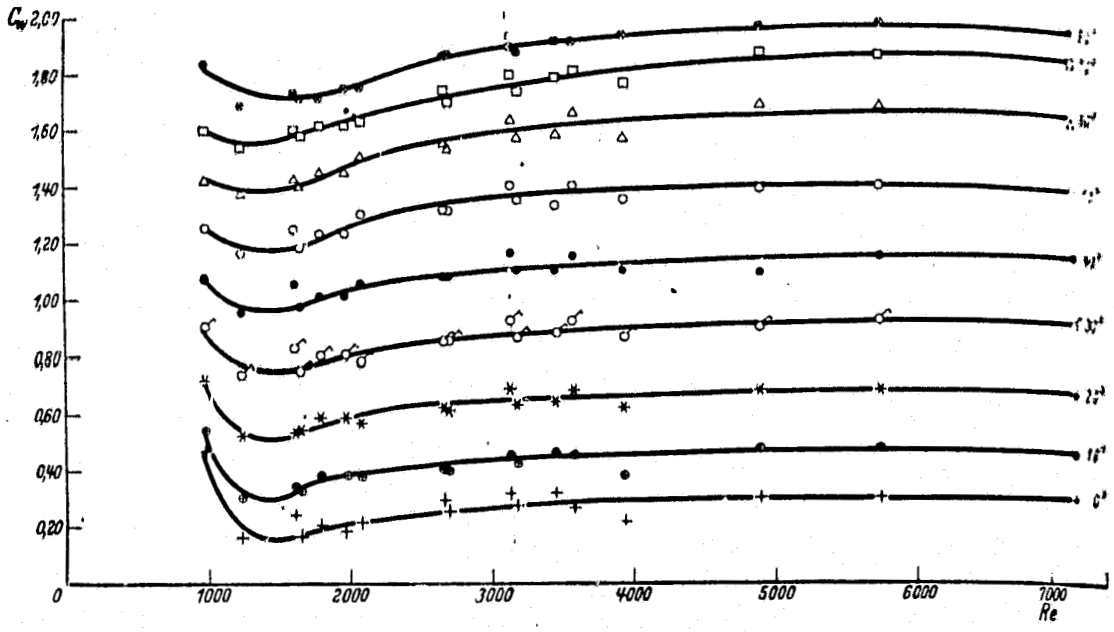

Fig. 23. Resistance coeefficient c_w of flat plates with angles of incidence between 0° and 90°.

When the plate width was set perpendicular to the flow direction as the length dimension we were not able to obtain a curve from the plotted resistance points.

Our values for Re 5,000 agree qualitatively with the resistance coefficients which were obtained by Fage and Johansen [16] from measurements of pressure distribution on the plate at Re 150,000 as a function of the angle of incidence.[1]

---

1. From measurements on plates of various widths Fage and Johansen showed that resistance coefficients are a function of the ratio tunnel width/plate width (which Glauert had already hinted at previously on the basis of theoretical considerations) and from this they extrapolated c_w for an infinite tunnel diameter. Accordingly, c_w for a plate perpendicualr to the flow (= 90°) is reduced by 13.5 percent. For $\theta = 30°$ the amount of probable reduction is 8 percent.

Using these two values we interpolated the amount of correction for the remaining angles of incidence and compared the values of Fage and Johansen reduced in this way with our c_w values in Fig. 22.

In light of the corrected Fage and Johansen values it can be said in evaluating our measurements that even for the unfavorable case (tunnel width/plate width ~ 86) the correction would be less than 1 percent, hence it can be ignored.

The maximum of their c_w curve, i.e. the resistance coefficient for the plate perpendicular to the flow, is 6.6 percent lower than the maximum c_w value of our curves. At about $\Theta = 60^0$ the /496 c_w value approaches ours to within 3.2 percent and then as the angle decreases the difference increases to 20 percent at $\Theta = 30^0$. Measurements at smaller angles were not available for comparison.

7. Calculation of the Resistance Coefficient according to the Karman Equation

From the vortex frequencies and distances between successive vortices measured by us the resistance of a plate perpendicular to the flow could be computed by means of a given Karman [4] relationship and compared with the resistance which had been measured directly. According to von Karman, by applying the impulse theorem to the flow of the vortex street, it follows that:

$$c_W = 2\left[0{,}799\,\frac{u}{U} - 0{,}323\left(\frac{u}{U}\right)^2\right]\frac{L}{D}.$$

The terms are defined as follows:

$$c_W = \frac{W}{\frac{\varrho U^2}{2} D},$$

u = velocity of the vortex system,
U = velocity of the body
L = distance between successive vortices
D = plate width
W = resistance per unit length
ρ = thickness.

The values of $\frac{u}{U}$ can be found from the vortex frequency N and the distance between successive vortices L from the equation

$$\frac{u}{U} = 1 - \frac{NL}{U}.$$

In our case of a body at rest in the flow, U is the velocity of the flow of the body (relative velocity of the body against the fluid flowing against it) and u is the relatvie velocity of the vortex against the flow. C_W is calculated for the Reynolds

numbers at which the frequencies N were measured (cf. II, 3a). The corresponding distances between vortices were taken from the mean curve of Fig. 16. The c_W values obtained in this way are plotted separately in Fig. 21. The path of these values with the Re number agrees qualitatively with the measured c_W values. On average, however, they are about 20 percent lower. This difference may perhaps seem somewhat strange. However, a comparison of our c_W values - calculated from the vortex street - with the corresponding values which von Karman and Rubach obtained in a water flow, shows that both are about equal: for Re = 1,750 to 4,189 von Karman and Rubach got a mean c_W value of 1.60, and our computed c_W values in this region from 1.50 - 1.60 rose to a constant end value.

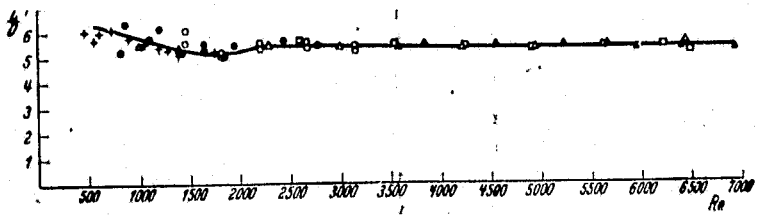

Fig. 16. Distances between successive vortices on plates perpendicular to the flow (about 6 plate widths behind the plate).

- $D = 0{,}160$ cm
- $D = 0.270$ cm
- $D = 0{,}343$ cm
- $D = 0{,}395$ cm
- $D = 0{,}600$ cm
- $D = 0{,}750$ cm
- $D = 0{,}795$ cm

Measurements of Fage and Johansen (at greater Re values: Re 150,000) yielded differences in c_W values from the vortex street or pressure distribution of about the same magnitude as ours. To try to reduce this difference with Fage and Johansen by correcting only the c_W values from the pressure distribution because of the finite tunnel diameter does not seem to us to make much sense. /497

On the whole, then our measurements and earlier ones calculated from the vortex street give a c_W value about 20 percent lower in comparison with c_W values found in other ways (weighing, pressure distribution).

Chapter IV. Summary

1. The dimensionless vortex frequency $\frac{ND}{U}$ is measured

for circular cylinders perpendicular to the flow in the range of Re numbers 50-1,350 and for inclined cylinders in the range 65-240. Two acoustical methods were used for determining frequencies: detecting the resonance tones of the cylinders (wires) and listening by means of a Pitot tube. With increasing Re $\frac{ND}{U}$ at first showed a sharp rise followed by a more gradual increase. The curve is nearly a mirror image of the familiar c_W curve (including one or two dips). For inclined cylinders $\frac{ND}{U}$ increases with increasing angle of incidence.

2. For flat plates perpendicular to the flow in the region Re = 500 to 7,500 vortex frequencies and distances between successive vortices were measured with a Pitot tube and resistances were measured with a balance. Up to Re = 1,500 there is a rise in $\frac{ND}{U}$ values and a fall in c_W values. At Re = 1,500 the frequency reaches a maximum with $\frac{ND}{U} = 0.157$ and the resistance coefficient reaches a minimum with $c_W = 1.72$. Beyond this point $\frac{ND}{U}$ declines and c_W rises. Both become more or less constant from Re = 5,000 on, with $\frac{ND}{U} = 0.147$ and $c_W = 1.97$. Also for the distances between vortices $\frac{l}{D}$ there is a weak minimum at Re = 1,500. A constant end value of $\frac{l}{D} = 5.4$ at about Re = 4,000 is assumed. The c_W values calculated after von Karman from the frequencies and distances between vortices give the same curve as a function of Re as the experimental values but they are about 20 percent lower.

3. As the angle of incidence decreases (90°) $\frac{ND}{U}$ increases and c_W decreases. The dependence on Re corresponds to that when the plates are perpendicular to the flow.

4. Vortex frequency and distance between successive vortices turn out to be functions of the distance from the plate. Closer to the plate smaller distances between vortices and higher frequences are observed than somewhat further away from the plate.

The above study was done in the Department of Applied

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Mechanics and Thermodynamics at the Physical Institue of the University of Leipzig.

I owe very special thanks to my respected teacher, Prof. Dr. Schiller, for his encouragement in this work and for his continued support. I am also grateful to Dr. Naumann for his helpful support and to chief technician Hentsch for doing the mechanical work.

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